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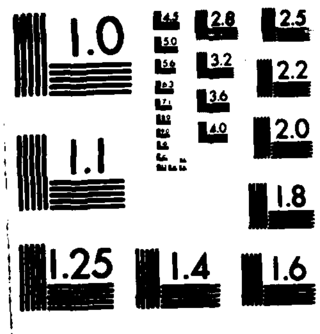

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ROYAL SIGNALS AND RADAR ESTABLISHMENT

Memorandum 3765

Title: MOON BOUNCE COMMUNICATIONS TO SMALL TERMINALS

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Date: October 1984

SUMMARY

The object of this study is to investigate the feasibility of communications from a large fixed earth station to a small mobile station using moon-reflected signals. A review of the technical problems is presented, and recommendations made on the choice of operating frequency, modulation type and equipment. Suggestions are made for practical trials, using equipment which is already in existence at RSRE Defford.

RSRE MEMORANDUM NO 3765

MOON BOUNCE COMMUNICATIONS TO SMALL TERMINALS

G E James

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1 INTRODUCTION

The object of this study is to investigate the feasibility of communication from a large fixed earth station to a small mobile station using moon-reflected signals. The availability of equipment at RSRE Defford is among the factors considered. After a consideration of factors influencing system performance, some suggestions are made for practical trials.

2 CHOICE OF FREQUENCY

Bearing in mind the equipment available at RSRE Defford, the following possibilities are suggested:

i. Using the 40 foot dish at a frequency of around 8 GHz.

ii. Using the 80 foot dish at a frequency of around 2.5 GHz.

iii. Using the 80 foot dish at a frequency of around 300 MHz.

In making the calculations it will be assumed that 10 kW of transmitter power is available in each case and, since the requirement is for a small, easily concealed receiver, the physical size of the receive antenna will be kept the same in each case. The effects of the choice of frequency will now be considered:

a. The Uplink Loss

The moon subtends an angle of approximately ½ degree at the earth's surface, which may be less than the beamwidth of the transmitting antenna, in which case the uplink loss is very small, being just the power in the antenna sidelobes, and the atmospheric attenuation. If the antenna beamwidth is greater than the angle subtended by the moon, the loss will be given by

$$Lu = 20 \log \left(\frac{\theta_b}{\theta_m}\right) \qquad (1)$$

where θ_b = beamwidth
θ_m = angle subtended by moon

The 3 dB beamwidth of a uniformly illuminated circular aperture is given by

$$\theta b = 116 \ (\lambda/D) \text{ degrees} \tag{2}$$

where D = diameter of aperture
λ = wavelength

i. F = 8 GHz, D = 40 feet
Equation (2) gives $\theta_b = 0.36°$

ii. F = 2.5 GHz, D = 80 feet
Equation (2) gives $\theta_b = 0.58°$

iii. F = 300 MHz, D = 80 feet
Equation (2) gives $\theta_b = 4.8°$.

Thus with frequencies of 2.5 GHz or 8 GHz, the beamwidth is comparable with the angle subtended by the moon, but at 300 MHz the beam is ten times as wide as the moon, giving an uplink loss of 20 dB from equation (1).

b. The Reflectivity of the Moon

There have been many experiments to determine the reflective characteristics of the moon. Evans and Hagfors[1] summarised these results, expressing the radar cross section (σ) as a fraction of the physical cross section of the moon. Over the wavelength range one centimetre to ten metres they found no clear wavelength dependence, and the mean of the values obtained for σ was 0.07.

There is some evidence for a wavelength dependence in the distribution of scattering areas across the moon's surface, in that at 1 metre wavelength the moon reflects predominantly from the centre of the visible disc while at 1 cm wavelength the disc appears more uniformly bright. This would only affect the total reflected power if the antenna beamwidth was much less than the angular extent of the moon, which is not true in any of the cases being considered.

c. The Down Link Loss

Since it has been decided to keep the physical size (strictly the effective area) of the receiving antenna the same in each frequency case, the downlink loss will be independent of frequency, the received power being given by

Pr = Power flux density x Effective area of receive antenna

$$= \frac{P_m A_e}{4\pi d^2} \tag{3}$$

where d = distance from moon to earth
P_m = power reflected by moon.

In conclusion therefore, 300 MHz using an 80 foot dish is ruled out by the 20 dB uplink loss, and there is likely to be little difference in performance between the other two cases studied.

3 CALCULATION OF RECEIVED SIGNAL/NOISE DENSITY RATIO (C/kT)

Using a frequency of 8 GHz, a 40 foot transmit antenna and a 10 kW transmitter, and assuming negligible uplink loss and a 7% reflectivity as discussed above, the power reflected by the moon is

$$P_m = 0.07 \times 10 \text{ kW}$$

$$= 700 \text{ W}$$

$$= 28.5 \text{ dBW}$$

The signal to noise density at the receiver will be

$$C/kT = P_m - L_d + G_r - kT \tag{4}$$

where $L_d = 20 \log \frac{4\pi d}{\lambda}$

G_r = gain of receive antenna

T = receiver noise temperature

k = Boltzmann constant.

The mean moon-earth distance d is 384000 km, and the wavelength λ is 3.75 cm, giving a downlink loss of $L_d = 222.5$ dB.

A small antenna developed for mobile communications by British Aerospace for RSRE has a gain of 4.5 dB at 8 GHz.

Taking k = -228.6 dBW/Hz/K and T = 300K,

$$C/kT = 28.5 - 222.5 + 4.5 + 228.6 - 25$$

$$= 14 \text{ dB Hz}.$$

For reasons discussed above, the use of the 80 foot dish at a frequency of 2.5 GHz will give a similar result, if the physical size of receiving antenna is unchanged. It should be noted that the figure derived above is only approximate, due to uncertainty in the value of the moon's reflectivity, and that no margin has been allowed for atmospheric attenuation of the signal.

4 EFFECTS OF DOPPLER SHIFT

There are two sources of Doppler shift. One is the rotation of the earth which gives the transmitting and receiving stations a component of velocity in the direction of the moon. The other is due to the ellipticity of the moon's orbit, which means that it has a component of velocity in the direction of the earth. These velocity components have maximum of $\pm$ 500 m/s and $\pm$ 80 m/s respectively(1) for stations on the equator. Since there is a Doppler shift on each leg of the round trip, the maximum Doppler shift is given by

$$\frac{\Delta F}{F} = \frac{2V}{C}$$

for F = 8 GHz, ΔF max = $\pm$ 30 kHz; and

for F = 2.5 GHz, ΔF max = $\pm$ 9.4 kHz.

Since the signal to noise density is low, the receiver cannot simply operate with a predetection bandwidth sufficiently wide to encompass this Doppler shift, so some form of frequency tracking will be required in the receiver. Since the rate of change of Doppler is quite slow this should cause no major problems.

5 MULTIPATH FADING

If the moon is regarded as an assembly of scattering elements distributed randomly over its surface, the intensity of the echo at any instant is determined by the resultant of the signals scattered by each element. This intensity would be constant if the moon always presented the same face to the observer, so that the phase relationship between the components was unvarying. In fact the moon librates, or rocks about on an axis which changes with time. This libration leads to a changing phase relationship between the components of the echo, and hence to severe multipath fading.

There are four components to the libration of the moon:

i. Libration in Latitude, L_B

The moon's equator is inclined to the phase of its orbit by about 6.5°, so that as the moon orbits the earth, the centre of the lunar disc as observed from the earth varies in lunar latitude by $\pm$ 6.5°. This component therefore has a period of one sidereal month, and reaches a maximum value of 3×10^{-7} rads/sec, which occurs when the moon crosses the nodes of its orbit.

ii. Libration in Longitude, L_l

The moon rotates about its own axis at a constant rate equal to its mean geocentric angular velocity, but since the orbit is elliptical the geocentric angular velocity will not be constant. The libration in longitude is caused by the difference between the instantaneous geocentric angular velocity and the angular velocity about the moon's axis. This reaches a maximum value of 4×10^{-7} radians/sec, at apogee and perigee.

iii. The Diurnal Libration, L_D

As the earth rotates, an observer at its surface sees a parallactic shift between the centre of the moon's projected disc and the true centre of the moon. This diurnal libration reaches a maximum value with the moon at transit, with declination 0° of $12 \cos \psi \times 10^{-7}$ radians/sec, where ψ is the latitude of the observer.

iv. Physical Libration

This is the rocking of the moon produced by the variable gravitational couples exerted by the sun and the earth on the moon's equatorial bulge. Its maximum value is about 7×10^{-10} radians/sec, so may be neglected in comparison with other librations.

It can be shown(2) that the total libration is given by

$$L^2 = (L_1 + \delta_o \cos S_o)^2 + (L_B + L_D \sin\delta_o \cos\theta)^2 \qquad (5)$$

where δ_o = greatest declination reached by moon;

θ = difference between the longitude of the moon and the mean longitude of the ascending node.

For an observer on the equator, equation (5) gives a maximum total libration of around 16×10^{-7} radians/sec.

The differential Doppler shift of a scattering centre is given by

$$\Delta F_D = \frac{2FrL}{c}$$

where F is the frequency and r is the distance of the scattering centre from the axis of libration. For a frequency of 8 GHz, the range of differential Doppler shift is thus $\pm$ 150 Hz. This Doppler spread will give rise to a fading rate given by(3) the approximation

$$N = 0.67\ (\Delta F_D)\ \max$$

For a frequency of 8 GHz therefore the maximum fading rate will be around 100 per second. For a frequency of 2.5 GHz, the maximum fading rate will be about 30 per second.

6 PROPOSED MODULATION METHOD

As the signals reflected from the moon will be subject to fast fading as described above, some form of diversity must be used. Weston(4) used five-fold frequency diversity with linear addition of diversity channels, which proved adequate. In the same experiments frequency shift keying was used, firstly binary and later four and sixteen level, the multi-level systems giving superior performance.

Taking Weston's results for five fold diversity using 16 level FSK, to obtain an error probability of 10^{-3} requires an energy/bit to noise/hertz ratio of 13 dB. Returning to the calculations in section 3, the maximum signal to noise density using the currently available equipment is 14 dB Hz. Thus even if a data rate of two bits per second is employed, the error rate will be worse than 10^{-3}.

The other problem encountered by Weston, namely inter-symbol interference due to moon delay distortion is of little concern here, since the low data rates forced by signal to noise considerations mean that the symbol period will be much larger than the maximum delay distortion of 11.6 ms.

It should be noted that while Weston's experiments used frequency diversity, the results obtained for energy per bit to noise per hertz ratio are also valid for time diversity of the same order. This is because frequency diversity divides the total transmitter power into n channels, whereas time diversity involves sending each information bit n times, giving a signalling bit rate of n times the information rate, so that the energy per bit is the same in each case. There being no intrinsic differences between time and frequency diversity, the choice will depend on practical considerations such as the availability of equipment.

In view of the above, and taking into account the current state of modem development at RSRE, the following modulation schemes are proposed.

i. If a larger antenna is constructed, bring the signal to noise density ratio up to around 21 dB Hz, it may be possible to operate at 16 bits/second, using 64 level differentially encoded FSK. In this mode there are six repeats of each character, which should provide sufficient diversity to overcome multipath fading.

ii. If the above is found not to give adequate performance, then 2 bits/second transmission can be used. In this case binary FSK is used, with 1:2 convolutional coding with a constraint length of five. This system may just work using the British Aerospace antenna at 8 GHz, and would probably be a worthwhile first trial as the equipment is already in existence.

In each case the demodulator is FFT based, and the modem has frequency tracking which can comfortably cope with the Doppler shifts in moon bounce communications.

7 CONCLUSIONS

Firstly, there seems little point in using frequencies in the UHF band due to the extremely large transmitting antennas which would be needed to make the beamwidth less than the angular extent of the moon and so minimise uplink loss. If the frequency is high enough to enable the antenna beamwidth to be less than the angular extent at the moon, then there is little variation in performance with frequency as the reflectivity of the moon does not vary over the useful range of frequency.

Regarding the choice between operation at 8 GHz using the 40 foot dish, and at 2.5 GHz using the 80 foot dish there is little difference in terms of the performance which may be expected, but there are other practical considerations. All equipment needed to operate at 8 GHz, including the receive antenna exists at Defford, and for this reason it may be sensible to use this for preliminary trials. However, for extended trials the availability of the 40 foot dish would become a major problem, as it is the main satcom antenna at Defford, and the use of the 80 foot dish at frequencies around 2.5 GHz would become attractive.

While there are some difficulties associated with Doppler and fading effects, the limiting factor is clearly the poor signal to noise ratio at the receiver. If it is desired to use the antenna developed by British Aerospace (or one of similar physical size at another frequency), then the signal-to-noise ratio at the receiver will give an error rate worse that 10^{-3} at a bit rate of 2 bits/seconds. Therefore it is recommended that a larger antenna is

used, such that the gain is increased by at least 5 dB. This system, using the modulation method outlined above, with five fold diversity, will give an adequate margin to allow communication at a rate of two bits per second with an acceptable error rate. It may be possible to operate at 16 bits/second using a larger antenna, but uncertainties, particularly in the exact value of the moon's reflectivity, make exact predictions difficult.

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